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13. ABSTRACT (*Maximum 200 words*)

A combined theoretical, computational, and experimental program has investigated situations where fluid motion and a flexible surface produce nonlinear interactions. The main cases of interest concern situations where an external flow field contains a significant disturbance, such as a vortex in subsonic flow or a shock wave in supersonic flow. This type of flow feature can produce pressure perturbations which may provoke movement in flexible panels on the surface , as well as unsteady viscous separation effects in the boundary layers, which are on all solid walls. The net result is a complex interaction between the external mainstream flow, the viscous boundary layers, and the flexible surface itself. The aforementioned interactions produce complicated oscillations of the surface that are sometimes referred to as limit cycle oscillations (LCO). When such events are observed, it is common for a significant flow disturbance, such as a shock wave or vortex, to be somewhere in the vicinity. The present research addresses a number of fundamental problems of LCO, with the goal of establishing cause and effect relationships in relatively simple environments. Several computational and experimental studies of selected simplified interactions are described in the body of the report.

14. SUBJECT TERMS

Limit Cycle Oscillations, Unsteady Separation, Deformable Surfaces, Vortex Dynamics, Shock Waves, Laminar Vortices, Turbulent Vortices, Vortex Interactions, Particle Image Velocimetry, Boundary Layers

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<u>**FINAL TECHNICAL REPORT**</u>

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COMBINED THEORETICAL AND EXPERIMENTAL STUDY OF PHENOMENA RELATED TO LIMIT CYCLE OSCILLATIONS

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Objectives

This research is a combined theoretical, computational and experimental study of the basic physics associated with limit cycle oscillations that are known to occur on an airframe surface. A central objective of the present research is to determine which generic features of an external flow field can induce deformations of the surface and under what circumstances. The main focus of the experimental work is on vortices in subsonic flow and their influence as a stimulus for movement of the surface; the theoretical and computational work considers this situation, as well as the influence of shock waves on a flexible surface in supersonic flow. Shock waves, vortices and a moving wall are all capable of inducing unsteady separation in the viscous boundary layer on the surface and thereby producing sharp changes in the local pressure distribution. The complex coupling that can occur between the boundary layer, the generic features in the external flow, and the moving (or deformable) surface is under study.

Status of Effort

The theoretical and computational research has focused on two types of surfaces, namely: (1) an elastic deformable wall of infinite extent and (2) a finite-length plate which is clamped at both ends. Various models for these types of surfaces have been considered. The infinite wall is studied as the simplest type of deformable wall that can model a local interaction, which is not complicated by reflected waves that may occur at the support locations of a finite length plate. In subsonic flow it has been shown that a moving vortex can have a dramatic effect on the contour of the wall and act to rapidly promote boundary-layer separation. The boundary-layer separation itself is found to produce sharp local changes in the pressure, and these in turn can provoke movement of the surface; solutions have been obtained to model this situation and these show how the disturbance is transmitted along the surface.

A method has been developed to study the deflection of a finite plate exposed to the movement of a vortex above. Calculated solutions of the model problem show that strong non-linear effects rapidly lead to limit cycle behavior and eventually chaotic (but bounded) motion of the plate.

In the experimental program, techniques were developed for accurately examining the overall motion of a deflecting surface in response to controlled vortex interactions in a low-speed water flow. A method employing digitally-enhanced image processing of a shadow moiré techniques have been developed, and the necessary software to allow interrogation and assessment of three-dimensional, time-varying surface deflections has been written and implemented. A test section has been developed which allows the examination of various types of vortex and boundary layer flows over a flat, deformable elastic surface; initial tests with transverse vortices have been run and evaluated; studies using axisymmetric "ring" vortices will follow on the transverse vortex studies. A calibration device for establishing the degree of deflection relative to the applied force was

design, fabricated, and implemented to allow quantitative assessment the moiré images. The PIV (particle image velocimetry) system has been developed and adapted for the particular test section employed in this study, and has been applied to examine selected vortex flow patterns.

The influence of a deformable surface which is exposed to a shock wave in supersonic flow is also under study in the theoretical program. In general, a shock wave can provoke boundary-layer separation and in turn can lead to a local absolute instability and an abrupt transition to turbulence. The current work has demonstrated that this instability can be suppressed by a compliant surface. Extensive calculations for this situation have defined the stability boundaries and have also revealed the presence of new types of instabilities associated with separated flows.

Accomplishments/New Findings

(1) Solutions have been obtained for a general pressure pulse applied to a deformable surface which subsequently moves along the surface in subsonic flow. These solutions reveal that traveling waves are set up along the surface. Numerical solutions for the boundary-layer flow on the moving surface show that an unsteady separation effect is quickly provoked provided the initial disturbance is sufficiently large; this in turn leads to sharp local changes in the pressure distribution which provokes further deformations in the surface. These results suggest how unsteady separation phenomena at high Reynolds number on an airframe component can set up a complex oscillation of the surface and suggest a mechanism for self-sustaining oscillations.

(2) When a vortex is in motion above a wall, it induces a substantial perturbation in the pressure field near the surface which can cause a significant deformation of a flexible surface. Solutions have been obtained for the inviscid flow and shape of the deformable wall for a number of models of a flexible surface. In general, the vortex always acts to pull the surface toward it, and this has profound effects on the viscous response of the boundary layer. Boundary-layer solutions have been obtained, and it has been found that an unsteady separation effect occurs in all cases; furthermore, separation of the boundary layer is dramatically enhanced and strengthened by the presence of the deformable wall. This suggests that a sharp viscous response of the boundary layer will occur whenever a vortex is in proximity to a flexible wall in the form of local pressure spikes; furthermore, the presence of the flexible wall strengthens this response.

(3) For supersonic flow past a wall, the theoretical work has focused on a generic problem corresponding to the shock wave/boundary layer interaction that occurs near a compression ramp. Here the shock wave provokes separation of the boundary layer in the corner giving rise to a steady region of reversed flow provided the ramp angle (and therefore the strength of the shock) is not too large. Although supersonic flow is generally believed to be stable to small disturbances, it has been found that above a

certain critical ramp angle, the flow becomes unstable due to the appearance of an inflectional profile within the reversed flow region. The instability is absolute and presents itself as a stationary growing wave packet centered on the reversed flow region. This suggests that the separation bubble in the boundary layer is a potential site for a direct and abrupt transition to turbulence. In the present program, solutions have been obtained for this flow geometry but with a flexible wall; the approach utilized is high-Reynolds-number asymptotic theory and constitutes a full nonlinear interaction between the external flow, the boundary layer and the flexible surface. It has been found that the presence of the flexible wall stabilizes the flow and that steady reversed-flow solutions are possible up to much stronger shock strengths. At very high ramp angles, several other types of instabilities have been identified, and it has been shown how these can be stabilized through use of a flexible wall. This suggests that the presence of a compliant coating in supersonic flow has the potential to be useful in delaying transition to turbulence. Note that the present results have also been shown to apply to the case of hypersonic flow with strong wall cooling.

(4) The problem of a finite one-dimensional plate set in motion by the passage of a vortex in a uniform flow above the plate has been modeled, and calculations have been carried out to determine the plate response in a variety of situations. This problem has been considered as a predecessor to a full two-dimensional plate in which the response is expected to be much more complex. When the pressure stimulus due to the vortex is relatively weak, the plate response is weakly nonlinear and complex limit cycle behavior is found. On the other hand, as the vortex strength is increased, essentially chaotic but bounded vibrations of the plate occur.

(5) Initially, transverse vortices generated using a wall flap have been examined with the experimental test section. Particle image velocimetry (PIV) has been employed to successfully quantify the generated flow-field characteristics using a PIV system constructed in house (partially developed using funds from the grant); this system utilizes film recording in conjunction with a bias mirror, and a laser scanning illumination system. Using an autocorrelation analysis of the recorded images the local instantaneous, two-dimensional velocity field was established for selected flow conditions. Presently, PIV is being employed to examine the velocity and vorticity fields for a low Reynolds number transverse vortex passing over the test membrane. Initial experimental results indicate support of the computational results (see 2 and 3 above), indicating the development of a strong vortex-surface interaction which both modifies the immediate flow field, and creates strong localized pressure fields which interact strongly with the membrane.

(6) For the experimental test section, a program has been developed which utilizes sequential digitized video frames of the moiré pattern generated by the deflection of an elastic membrane to assess the spatial-temporal deflection of the membrane surface during the passage of an experimentally-generated transverse vortex. By computationally assessing the ordering of the moiré fringes, the out-of-plane motion of the membrane can be tracked and correlated with the vortex translation. Results

support the computational observation (section 2) that the magnitude of the sharp viscous response of the boundary layer created by a vortex passing in proximity to the membrane appears to be amplified by the presence of the membrane. The study of different vortex forms, as outlined in (5) above, will help establish the nature of this vortex-membrane interaction; however, it is clear that a symbiotic mechanism exists for a strong mutual interaction between vortices and flexible surfaces. The PIV results suggest that transverse vortices in proximity to a deformable boundary retain their integrity longer than the counter-part vortex in proximity to a solid surface. Initial simultaneous flow field-deformation studies have proven problematic because of cross-contamination of the flow-field lighting technique by the shadow moiré lighting. Methods for reducing or elimination of this lighting contamination are being examined; when successful, these simultaneous studies will allow the experimental correlation of the local vortical flow field and with the local surface deformation.

Personnel Supported

Professor J. D. A. Walker
Professor C. R. Smith
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Publications

Doligalski, T. L., Smith, C. R. and Walker, J. D. A. 1994 "Vortex Interactions with Walls", *Annual Review of Fluid Mechanics* **26**, 573-616.

Seal, C. V., Smith, C. R., Rockwell, D. 1995 "Dynamics of the Vorticity Distribution in End-wall Junctions", Paper No. AIAA 95-2238, San Diego, Ca. Also in review, *AIAA Journal*.

Smith, C. R. 1996 "Coherent Flow Structures in Flat Wall Turbulent Boundary Layers: Facts, Mechanisms, and Speculation," Keynote paper in Coherent Flow Structures in Open Channels, P. J. Ashworth, J. L. Best, S. J. Bennett, and S. J. McLelland eds., John Wiley & Sons.

Kiran, A. S., Varley, E. and Walker, J. D. A. 1996 "Unsteady Motion Induced on a Flexible Surface at High Reynolds Number", AIAA Paper 96-2138, 1st AIAA Theoretical Fluid Mechanics Meeting, New Orleans, June, 1996; expanded journal article in preparation.

Zhikharev, C. N. and Walker, J. D. A. 1996 "The Influence of a Flexible Surface on Supersonic Boundary-Layer Stability", invited paper, 19th International Congress of Theoretical and Applied Mechanics, Kyoto, Japan, August 1996; journal article in preparation.

Kiran, A. S., Varley, E. and Walker, J. D. A. 1996 "The Influence of Vortex Motion on a Flexible Surface and Boundary-Layer Separation", journal article, in review.

Walker, J. D. A., Delph, T. J. and Zhikharev, C. N. 1997 "Vortex and Separation Induced Oscillations of a Finite Plate", invited paper, AIAA Aerospace Sciences Meeting, Reno, Nevada, January, AIAA 95-0575; to appear in the *Journal of Guidance, Control and Dynamics*.

Interactions/Transitions

a. Meetings

"The Influence of a Deformable Wall on Instability in Supersonic Flow on a Compression Ramp", J. D. A. Walker and C. N. Zhikharev, 48th Annual Meeting, Division of Fluid Dynamics, American Physical Society, Nov. 19-21, 1995.

"Coherent Flow Structures in Turbulent Boundary Layers: Facts, Hypothesis, Speculation," C. R. Smith, Invited Seminar, NASA Langley Flow Physics Branch, Langley, Virginia, 17 July, 1995.

"Turbulent Wall Layer Vortices", J. D. A. Walker, Invited Speaker at Naval Undersea Warfare Center, Newport News, Rhode Island, April 15, 1994.

"Vortex Interactions with Walls", J. D. A. Walker, Invited Keynote Speaker, 3rd Army Research Office Workshop on Rotational Aerodynamics, Georgia Institute of Technology, March 24-25, 1994.

"Unsteady Boundary-Layer Separation", J. D. A. Walker, Invited Seminar, City College, New York, October 3, 1995.

"Flow Structure in End-Wall Boundary Layers: A Study in Complex Vortex Dynamics", C. R. Smith, Invited Seminar, Brown University, 4 December 1995.

"Unsteady Motion Induced on a Flexible Surface at High Reynolds Number", J. D. A. Walker, presentation at 1st AIAA Theoretical Fluid Mechanics Meeting, New Orleans, June, 1996.

"Combined Theoretical and Experimental Study of Phenomena Related to Limit Cycle Oscillations", J. D. A. Walker, AFOSR Contractors' Meeting, Virginia Beach, June, 1996.

"Basic Research Issues", J. D. A. Walker, AFOSR Contractors' Meeting, Virginia Beach, June, 1996.

"The Influence of a Flexible Surface on Supersonic Boundary Layer Instability", J. D. A. Walker, 19th Congress on Theoretical and Applied Mechanics, Kyoto, Japan, August, 1996.

"Experimental Measurement of Deformation and Motion of a Flexible Panel via Shadow Moire Technique," C.R. Smith, 49th Meeting of Amer. Phys. Soc., Syracuse, NY, Nov., 1996.

b. Consultative/Advisory

Smith, C. R. Consultant, Flow Physics Branch, NASA Langley. 17-19 July 1995. Consultation on noise generation by vortices, and turbulent flow structure. Contact persons: Barry Lazos, Bart Singer, Tom Gatski

New Discoveries, Inventions or Patent Disclosures

None

Honors/Awards

Honor/Award: Fellow, American Physical Society — Year Received: 1991
Honor/Award Recipient(s): J. David A. Walker
Awarding Organization: American Physical Society

Honor/Award: Associate Fellow, AIAA — Year Received: 1993
Honor/Award Recipient: J. David A. Walker
Awarding Organization: American Institute of Aeronautics and Astronautics

Honor/Award: Alexander von Humboldt Senior Scientist — Year Received: 1994
Honor/Award Recipient: J. David A. Walker
Awarding Organization: Alexander von Humboldt Foundation

Honor/Award: Chairman, AIAA Fluid Dynamics Technical Committee
Year Received: 1993-1996
Honor/Award Recipient: J. David A. Walker
Awarding Organization: American Institute of Aeronautics and Astronautics

Honor/Award: Keynote Speaker, Conference on Coherent Flow Structures in Open Channels
Year received: 1995
Honor/Award Recipient: C. R. Smith
Awarding Organization: British Sedimentological Research Group